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HARDWARE IMPLEMENTATION OF FUZZY MAXIMUM POWER POINT TRACKING THROUGH SLIDING MODE CURRENT CONTROL FOR PHOTOVOLTAIC SYSTEMS

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Key words: Photovoltaic energy, Maximum power point tracking (MPPT), Fuzzy logic maximum power point (Fuzzy MPPT), Sliding mode current controller (SMCC).

This paper deals with an intelligent-robust control method for maximum power point tracking (MPPT) of photovoltaic (PV) system under irradiation conditions change. The proposed MPPT scheme incorporates an intelligent fuzzy controller with a robust sliding mode current controller to enhance the MPP pursuit performance (speed and accuracy tracking, steady state power oscillations). To prove the performance improvement of the proposed scheme, a comparison is performed experimentally with both conventional IncCon algorithm and conventional incremental through sliding mode current control under different irradiance levels. The results obtained through the developed prototype based on dSPACE DS1104 board demonstrate that this method provides better performance and more robustness to the MPPT in terms of power oscillations, convergence speed to the optimal point and accuracy tracking following irradiation changes.

1. INTRODUCTION

The world has been suffering from several environmental problems in the last decades (air pollution, global warming …etc.), this was due to the incontrollable massive use of oil and carbon as energy sources [1]. For this reason, clean energy sources were emerged like the suitable solution in order to overcome the present problems [2–4], they possess inherent benefits towards the environment. Solar energy is the most commonly used power source through photovoltaic (PV) arrays systems. However, those systems still do not provide the required efficiency while their performance depends on different factors such as temperature, shadow, dirtiness and spectral sunlight characteristics. The random variation of these factors will reduce the PV array output power [4].

In order to enhance the efficiency of the PV array systems, many techniques have been proposed to force the PV array systems to generate the maximum output power under the environmental and operational conditions change. The conventional MPPT (Maximum power point tracking) algorithms such as perturbation and observation (P&O) [2] or Incremental conductance (IncCon) [3–5] are intensively investigated during the last few decades. In P&O algorithm, the voltage is being increased or decreased with a fixed step size in order to reach the MPP. The weakness of this algorithm are: low speed tracking, loss of tracking direction and large oscillations around the MPP. In IncCon algorithm, the slope of the PV power curve is observed to identify the MPP position, this latter will be reached when the slope is zero. The IncCon algorithm presents the same limitations as P&O algorithm.

To overcome the precedent drawbacks, several recent researches have been investigated to introduce the artificial intelligence (AI) techniques such as fuzzy logic control (FLC) [6–9] and neural networks (NN) [10], neuro-fuzzy networks (NFIS) [11], genetic algorithm (GA) [12], particle swarm optimization (PSO) [13]. As presented in [14, 15], the exploitation of these methods provides high performance MPP tracking. Specially, the FLC presented design simplicity and easy implementation compared to other AI methods.

On the other hand, some researchers were interested by the MPPT based on current oriented loop [16] and voltage oriented loop [17, 18]; the first one affords an accurate MPP tracking as well as a satisfactory reduction of oscillations around the MPP, owing to the linear relation between the PV array current and solar irradiation. The PI controller [16], the predictive controller [19-21] and sliding mode current controller (SMCC) [22] are among the most useful techniques. Sliding mode current controller has significant advantages such as robustness and implementation simplicity. Also it has a good performances (fast response and very low current ripples) compared to PI controller, in addition it does not require a load voltage sensor as the predictive controller.

In this work, a combination of intelligent fuzzy controller with a robust SMCC technique is proposed for improving performance compared to recent MPPT techniques. The performance of the proposed technique has been tested experimentally through a prototype developed based on dSPACE 1104, under irradiation changes. A comparison of the obtained results with both IncCon based SMCC and conventional IncCon MPPTs, is investigated in terms of power oscillations, speed and accuracy tracking. More details are addressed in the subsequent sections.

This paper is organized as follows. In Section 2, the proposed global system is presented. While, in the section 3, the proposed fuzzy-MPPT through SMCC is discussed. In section 4, the experimental results are discussed, and finally, in Section 5, conclusions are drawn.

2. SYSTEM GLOBAL CONFIGURATION

The global system consists of the main components: the PV array (A.), boost converter (B.), load (C.), MPPT unit (D.) and SMCC controller (E.), as shown in Fig. 1.

The power will be generated by the PV array depending on solar irradiation. The boost converter is used to track the MPP and to deliver it to the load permanently. The MPPT and SMCC units serve to drive the boost converter. The measured PV output current and voltage (i_{pv}, v_{pv}) are the MPPT inputs. Meanwhile, the MPPT output (i_{ref}) and the i_{pv} are the SMCC inputs. The SMCC delivers a binary output (S) which will control the boost converter switch.

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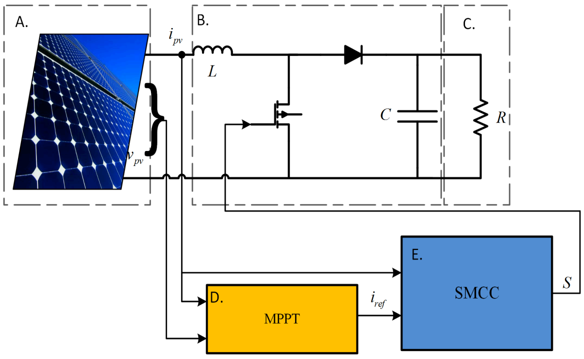

Fig. 1 – System global configuration.

3. GLOBAL SYSTEM CONTROL

Different modifications and improvements are being introduced recently to the current MPPT algorithm in order to develop new MPPT method with better performance. Therefore, the current IncCon algorithm proposed in [18] is modified by fuzzy logic control and combined with sliding mode current control technique in order to design an enhanced MPPT method.

3.1 CURRENT FUZZY MPPT

Recently, fuzzy logic control has been applied to design MPPT control system where robustness and design simplicity are required [6–9]. In this case, the knowledge of the exact model is not required. However it is necessary for the designer to have a complete knowledge about the PV behavior. For the present system illustrated in Fig. 2, the fuzzy MPPT has two inputs, the error $e(k)$ and the error change $\Delta e(k)$. The measured voltage v_{pv} and current i_{pv} at sampling time kT are used to calculate $e(k)$ and $\Delta e(k)$ as given below:

$$p_{pv}(k) = i_{pv}(k)v_{pv}(k) \tag{1}$$

$$e(k) = \frac{p_{pv}(k) - p_{pv}(k-1)}{i_{pv}(k) - i_{pv}(k-1)} \tag{2}$$

$$\Delta e(k) = e(k) - e(k-1) \tag{3}$$

where $e(k)$ represents the instantaneous position in the PV characteristics either right or left to the MPP and $\Delta e(k)$ is the moving direction of this instantaneous point. Where Δi_{ref} designates the current step size of the MPPT.

The linguistic variables of the fuzzy MPPT are defined as: (PB: Positive Big, PS: Positive Small, Z: Zero, NS: Negative Small, NB: Negative Big), the membership which relates the inputs and the output are depicted in Fig. 3. The fuzzy control rules are defined in order to guarantee the good variable step Δi_{ref} (big value when sudden irradiation, very small value in steady state) depending on the incremental current conduction behavior for attaining a speed tracking with less oscillation around the MPP. The fuzzy MPPT includes 25 rules as described in Table 1. When the inputs variables are converted into linguistic variables through fuzzificaion step, the output Δi_{ref} will be generated by the rules and Mamdani interface with a max-min operation fuzzy combination rule. In order to convert the output variable to numerical value, center of gravity method is used during defuzzificaion for this purpose as it is given by:

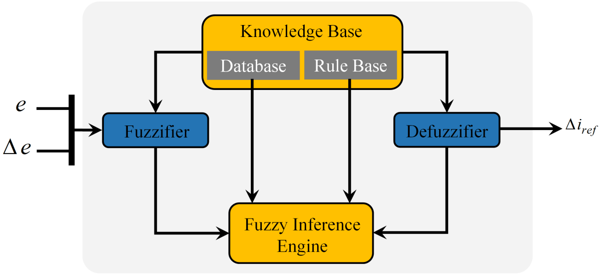

Fig. 2 – Bloc diagram of fuzzy MPPT.

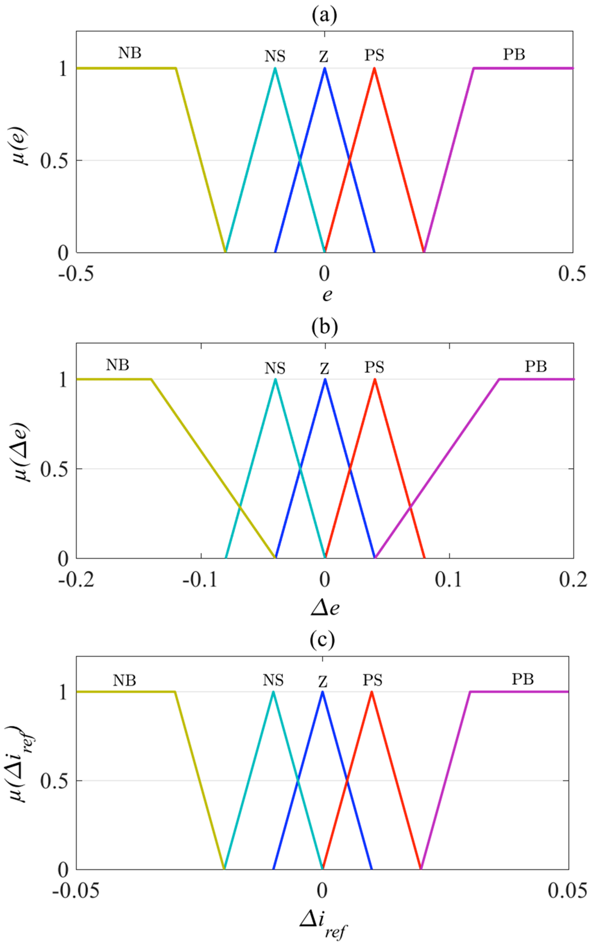

Fig. 3 – Membership functions. (a) Input of e, (b) Input of Δe and (c) Output of Δi_{ref}.

Table 1

Fuzzy MPPT rules

		e				
		NB	NS	Z	PS	PB
Δe	NB	PB	PS	Z	Z	Z
	NS	PB	PS	Z	Z	NS
	Z	PB	PS	Z	NS	NB
	PS	PS	Z	Z	NS	NB
	PB	Z	Z	Z	NS	NB

$$\Delta i_{ref} = \frac{\sum_{j=1}^{n} \mu(\Delta i_{ref_j}) - \Delta i_{ref_j}}{\sum_{j=1}^{n} \mu(\Delta i_{ref_j})}, \tag{4}$$

where n is the maximum number of effective rules, $\mu(\Delta i_{refj})$ is the weight factor, and Δi_{refj} is the value corresponding to the membership function of Δi_{ref}. Then, the current reference i_{ref} is obtained by adding the preceding value of i_{ref} to Δi_{ref} as follows:

$$i_{ref}(k) = i_{ref}(k-1) + \Delta i_{ref} \ . \tag{5}$$

3.2 SLIDING MODE CURRENT CONTROL

The role of SMCC is to enforce the i_{pv} to track the i_{ref} delivered by the MPPT unit. The control design is based on dc–dc boost converter model. Figure 4 illustrates the equivalent circuits of the boost converter considering on and off switching states.

The boost converter model equations can be described as follows:

$$\begin{cases} \dfrac{\mathrm{d}\, i_{pv}(t)}{\mathrm{d}t} = -(1-S)\dfrac{v_c(t)}{L} + \dfrac{v_{pv}(t)}{L} \\ \dfrac{\mathrm{d}\, v_c(t)}{\mathrm{d}t} = (1-S)\dfrac{i_{pv}(t)}{C} + \dfrac{v_c(t)}{RC} \end{cases}, \tag{6}$$

where S is the control switch states.

The surface of the SMCC is defined as follows:

$$\psi = i_{ref} - i_{pv} \ . \tag{7}$$

To enforce the PV array current i_{pv} to track the MPPT i_{ref}, the control S can be defined as:

$$S = \begin{cases} 1 & \text{if} \quad \psi < 0 \\ 0 & \text{if} \quad \psi > 0 \end{cases} . \tag{8}$$

In another words, the control structure is given by [23]:

$$S = \frac{1}{2}(1 - \mathrm{sign}(\psi)) \ . \tag{9}$$

The current loop stability is analyzed through Lyapunov function in order to verify the control structure, Lyapunov condition being defined as [24]:

$$V = \frac{1}{2}\psi^2 > 0 \qquad \text{if} \qquad \psi \neq 0. \tag{10}$$

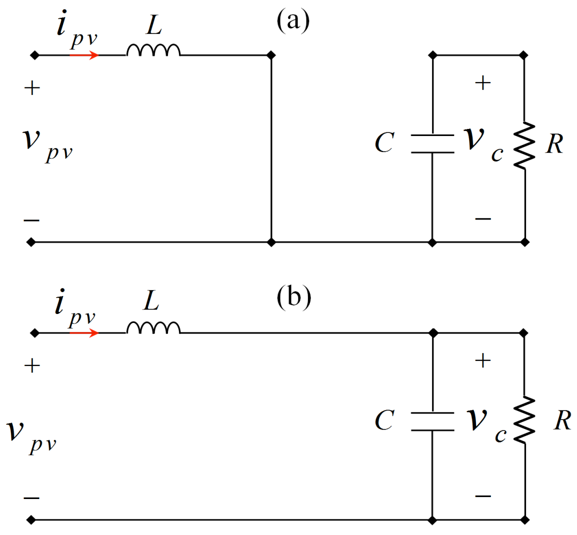

Fig. 4 – Equivalent circuit of the boost converter. (a) Switching on, (b) Switching off.

From equation (6), the derivative of equation (7) can be written as:

$$\psi' = i'_{ref} - i'_{pv} = -(1-S)\frac{v_c(t)}{\mathrm{L}} + \frac{v_{pv}(t)}{\mathrm{L}} - i'_{ref} \tag{11}$$

and from equation (11), the derivative of V can be expressed as:

$$\begin{aligned} V' &= \psi\psi' \\ &= \psi\left(\frac{-v_c(t)}{2L} - \frac{-\mathrm{sign}(S)v_c(t)}{2L} + \frac{v_{pv}(t)}{L} - i'_{ref} \right) < 0 \end{aligned} \tag{12}$$

The condition $V' < 0$ is verified when:

$$0 < v_{pv}(t) - L i'_{ref} < v_c(t). \tag{13}$$

Initially, the control current loop searches for reaching the sliding mode under initial conditions $i_{pv}(0) \geq 0$, $v_c(0) \geq 0$. When sliding mode is reached, $S \approx 0$ and $S' \approx 0$. Accordingly, $i_{pv}' \approx i_{ref}' \approx 0$. Since L is very small, then $L\, i_{ref}' \approx 0$. Knowing that, $v_{pv}(t) > 0$, $v_c(t)$ must be greater than $v_{pv}(t)$ in order to satisfy the inequality (13), which is verified for a boost converter (the output voltage is higher than the input voltage in steady state phase), consequently the stability of the control structure is achieved.

When the control signal S is implemented using the *signum* function, it will have a major problem which is the infinite switching frequency (Chattering phenomena) and this cannot be achieved in practice [25].Therefore, *signum* function must be replaced by hysteresis band in order to overcome this problem and to obtain an acceptable frequency variation as illustrated as follows:

$$S = \begin{cases} 1 & \text{when} \quad \psi < -\dfrac{1}{2}h \\ 0 & \text{when} \quad \psi > +\dfrac{1}{2}h \end{cases} . \tag{14}$$

The width (h) of the hysteresis band is used to limit the high speed changing state of the signal control S [25].This later will have an acceptable variable frequency and will provide a proper operation to the boost converter switch.

4. **EXPRIMENTAL RESULTS**

To evaluate and verify the efficiency of the proposed MPPT versus to IncCon through SMCC and conventional IncCon methods, experiments have been carried out under fixed temperature 25 °C and the parameters listed in Table 2. Figure 5 represents the power-voltage and current-voltage characteristics of the PV model panel.

As shown in Fig. 6, the experimental prototype includes a programmable dc power supply, SEMIKRON inverter, inductor, current sensor, resistive load, dSPACE DS1104, and 500 MHz Instek oscilloscope.

The real-time PV emulator and experimental test bench used were developed in LEPCI laboratory, University of Setif. As depicted in Fig. 7, the PV model with the MPPT control are implemented in Simulink environment. The first one generates the output PV voltage reference depending on the measured PV current which will be the voltage reference input of the programmable dc power supply [26, 27], while the MPPT controller drives the boost converter switch from the measured PV current and PV voltage reference. The interface between Simulink environment and the hardware prototype environment is handled through dSPACE DS1104 board.

The experiments for the three MPPT methods are carried out under periodically irradiation variation represented as: fixed at 500 W/m² then a sudden irradiation change from 500 to 1000 W/m^2, after slow irradiation change from 1000 to 500 W/m^2.

Table 2

System global parameters

PV Siemens SM110 electrical parameters	**Value**
Maximum power (p_{mpp})	110 W
Open circuit voltage (v_{oc})	43.5 V
Short circuit current (i_{sc})	3.45 A
Voltage at Pmax	35 V
Current at Pmax	3.15 A
Number of cells connected in parallel (*Np*)	1
Number of cells connected in series (*Ns*)	72
Number of modules connected in series (*Nss*)	2
Number of modules connected in parallel (*Npp*)	2
Boost converter electrical parameters	**Value**
Resistor (*R*)	50 *Ω*
Inductor (*L*)	40 mH
Capacitor (*C*)	1100 µF
Control parameters	**Value**
MPPT sampling time (*Ts_MPPT*)	0.001 s
SMCC sampling time (*Ts_SMCC*)	25 µs

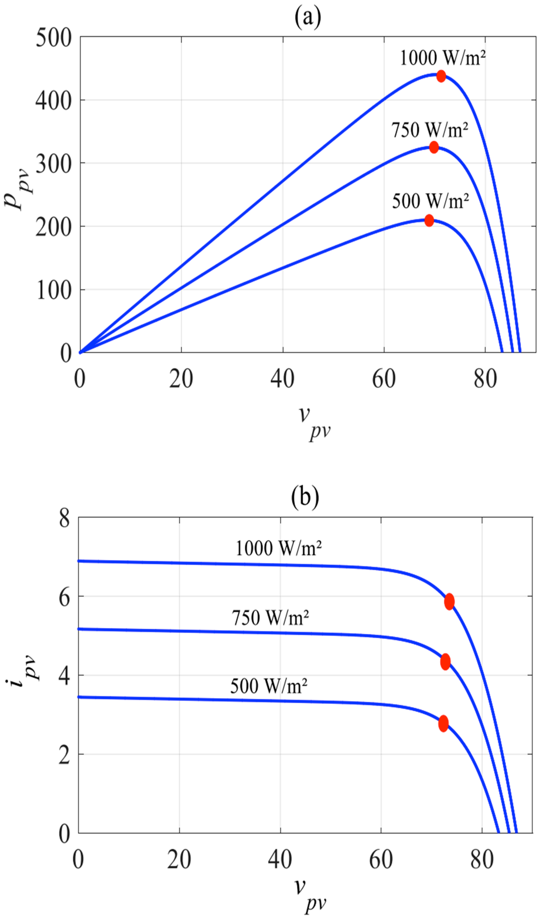

Fig. 5 – PV system characteristics. (a) p_{pv}-v_{pv}, (b) i_{pv}-v_{pv}.

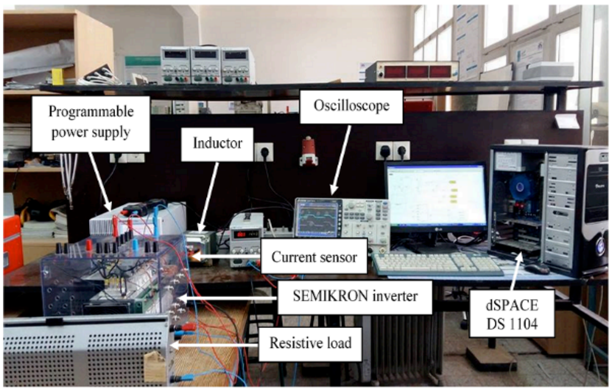

Fig. 6 – Snapshot of the experimental test bench.

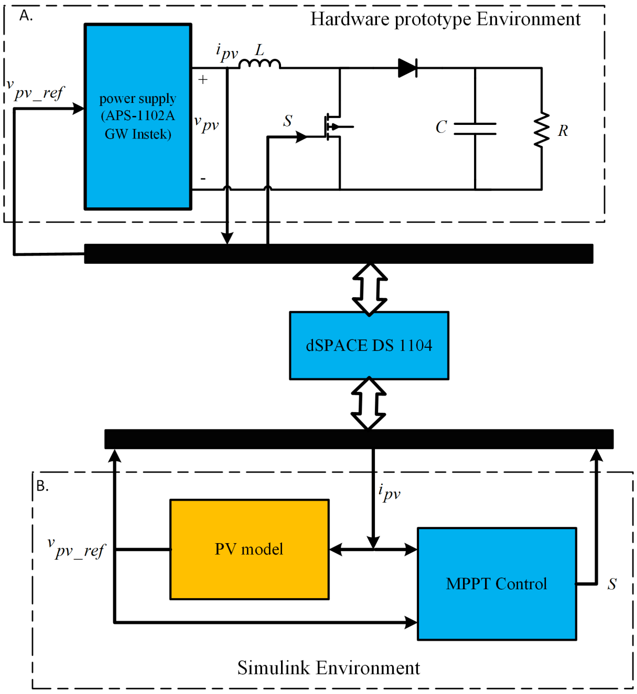

Fig. 7 – Experimental test bench flowchart.

The measured waveforms of the PV system employing the three considered methods are shown in Figs. 8, 9 and 10. It is clear that high dynamic performance is obtained from the proposed MPPT control compared to IncCon/SMCC and the conventional IncCon. Moreover, the proposed MPPT presented high accuracy tracking with less power oscillation. On the other side, the conventional IncCon exhibits large power oscillation, in addition, it shows some deviation in the tracking operation of MPP during the linear decrease of irradiance level. IncCon/SMCC provides a high accuracy tracking but with large oscillation as depicted in Figs. 8, 9, and 10.

IncCon/SMCC responds more swiftly and more accurately to the irradiation change than the conventional algorithm as shown by the experimental results, due to the linear relationship between the irradiance and PV current. While, the proposed MPPT is more efficient than IncCon/PCC in terms of convergence speed and oscillations due to the combination Fuzzy-MPPT. This is because it generates high Δi_{ref} following a sudden irradiation change and a small one for fixed or slow irradiation changes. Whilst, the conventional IncCon generates a fixed Δi_{ref} whatever the nature of change. Table 3 summarizes the difference between the tested MPPT techniques.

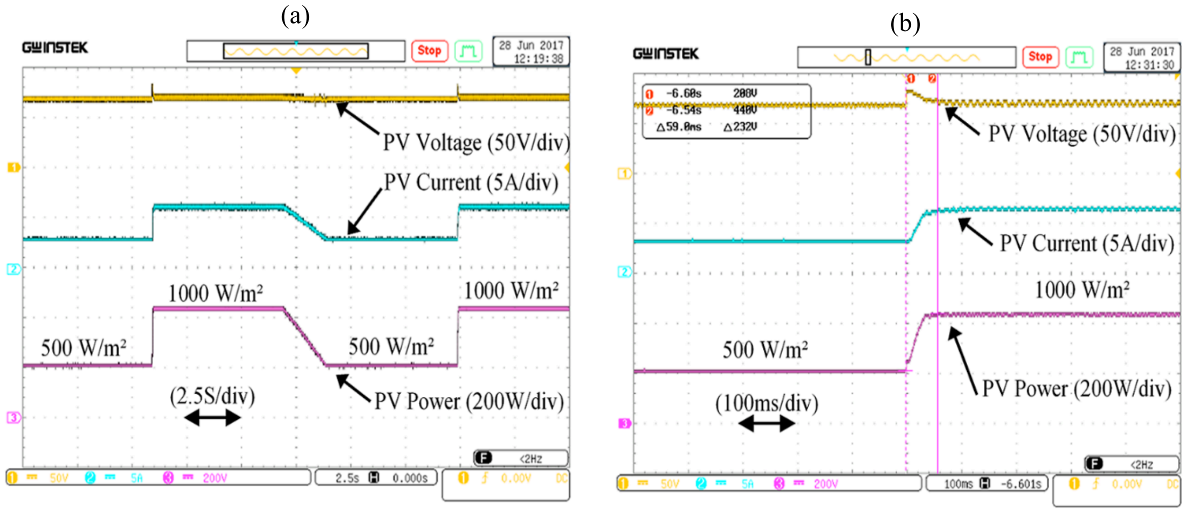

Fig. 8 – (a) Experimental results of the proposed MPPT, (b) Zoom results.

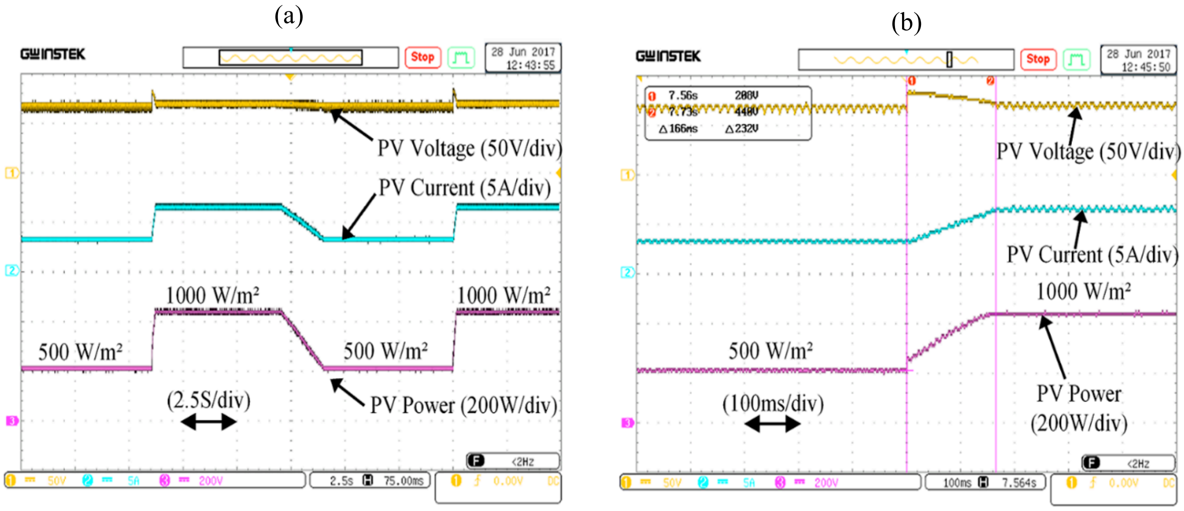

Fig. 9 – (a) Experimental results of IncCon/SMCC MPPT, (b) Zoom results.

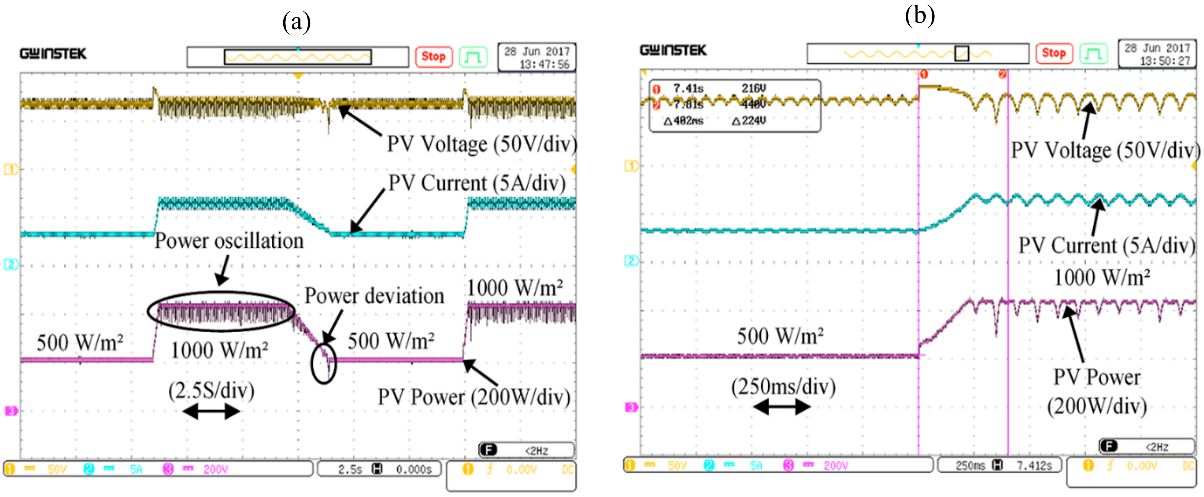

Fig. 10 – (a) Experimental results of conventional IncCon MPPT, (b) Zoom results.

Table 3

Comparative issues between different MPPT techniques

Feature	IncCon	IncCon/ SMCC	Proposed MPPT
Tracking speed time	High	Medium	Low
Steady state oscillation	Large	Small	Very small
Tracking accuracy	Bad	Good	Good
Implementation complexity	Lower	Moderate	Higher
Power efficiency	Low	Medium	High

5. **CONCLUSIONS**

In this paper, an intelligent-robust MPPT controller based on the combination of Fuzzy MPPT and sliding mode current control, is proposed. In order to demonstrate the efficiency of the proposed MPPT compared to IncCon/SMCC and conventional IncCon, experiments are performed through a prototype developed in laboratory which is based on dSPACE DS1104 board. The results obtained through this prototype confirm that the proposed technique can provide more robustness and better performance for the optimal point tracking in terms of oscillations power, convergence speed and accuracy resulting from any irradiation change. Where the proposed MPPT is 2.8 and 6.8 times faster than the conventional IncCon and IncCon/ SMCC algorithms respectively during fast irradiance variation.

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